1 OF 1

SAND 91-1926 C

Modulus Dispersion and Attenuation in Tuff and Granite

R.W. Haupt, R.J. Martin, III, X. Tang, W.J. Dupree
New England Research, Inc., White River Junction, VT

R.H. Price

Sandia National Laboratories, Albuquerque, NM

SAND--91-1926C

DE92 005459

Abstract: The effects of loading frequency, strain amplitude, and saturation on elastic moduli and attenuation have been measured in samples of the Topopah Spring Member welded tuff. Four different laboratory techniques have been used to determine Young's modulus and extensional wave attenuation at frequencies ranging from 10^{-2} to 10^6 Hz. The results are compared with data acquired for Sierra White granite under the same conditions. The modulus and attenuation in room dry samples remain relatively constant over frequency. Frequency dependent attenuation and modulus dispersion are observed in the saturated samples and are attributed to fluid flow and sample size. The properties of tuff were independent of strain amplitude in room dry and saturated conditions.

1 INTRODUCTION

The applicability of laboratory data for engineering purposes is a primary concern for design and licensing of the proposed nuclear waste repository at Yucca Mountain. Significant differences in elastic moduli and wave attenuation have been observed for a given rock, as measured with different laboratory and field techniques. These differences can be attributed to the time and strain amplitude dependencies in the anelastic response of rock to various loading conditions. Anelastic mechanisms in rock produce a phase lag of strain behind stress and affect the measured moduli and attenuation. The modulus, M , is represented by a complex quantity (Toksoz and Johnson, 1981),

$$M = M_R + iM_I \quad (1)$$

M_R and M_I are the real and imaginary parts of the modulus, respectively. The phase lag, ϕ , is a direct measure of the intrinsic loss or attenuation, Q^{-1} (Toksoz and Johnson, 1981),

$$Q^{-1} = M_I / M_R = \tan \phi. \quad (2)$$

1 This work was performed under the auspices of the U.S. Department of Energy (DOE), Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project, under Contract No. DE-AC04-76DP00789.

Several investigators have reported frequency, strain amplitude, and saturation dependences on M and Q^{-1} in crustal rocks (Gordon and Davis, 1968; Tittmann et al., 1977; Toksoz et al., 1979; Winkler et al., 1979; Spencer, 1981; Dunn, 1986; Paffenholz and Burkhardt, 1989). Different laboratory techniques were used to measure these dependences. Spencer (1981) used cyclic loading technique to examine the effects of frequency from 1 to 10^3 Hz and found that moduli and Q^{-1} changed dramatically with frequency in samples saturated with different fluids. Winkler et al. (1979) utilized this same method at frequencies less than 1 Hz to examine the effects of strain amplitude. He observed that moduli decreased and Q^{-1} increased with increasing strain amplitude in rock. Tittmann et al. (1977) used the resonant bar technique to examine these effects in vacuum dry and saturated samples at frequencies ranging from 1 to 200 kHz. He reported large variations in modulus and Q^{-1} as function of saturation. Toksoz et al. (1979), examined the effects of fluid saturation and confining pressure on Q^{-1} at ultrasonic frequencies.

In this study, Young's modulus and Q_E^{-1} are determined for the Topopah Spring Member welded tuff with several laboratory techniques over a large frequency band, 10^{-2} to 10^6 Hz. The effect of strain amplitude on these properties also is examined.

2 EXPERIMENTAL PROCEDURE

Young's modulus and Q_E^{-1} have been determined as functions of frequency, strain amplitude, and water saturation for two rock types, welded tuff and granite. Four techniques were used to cover frequencies ranging from 10^{-2} to 10^6 Hz. The strain amplitude dependence was measured at a single frequency, using a cyclic loading technique. Stress-strain hysteresis loops were generated at 0.1 Hz, with peak strain amplitudes that ranged from 10^{-7} to 10^{-4} .

The Topopah Spring Member welded tuff specimen was from Yucca Mountain, NV. The Sierra White granite specimen was from Raymond, CA. The porosities of the tuff and granite samples were 7.0% and 0.9%, respectively. Samples were vacuum dried for a 24 hour period and then allowed to equilibrate to room dry conditions. The specimens were tested in the room dry condition, then they were saturated with water and the measurement sequence was repeated. Saturated samples were jacketed with a cellophane sheath or Teflon tape to minimize evaporation losses. The techniques, corresponding frequency range, and sample dimensions are presented in Table I.

Table I.

TECHNIQUE	Frequency	Rock Type	Sample Dimensions (mm)	
			length	diameter
Cyclic loading	0.01 - 100 Hz	tuff	210	55
		granite	305	152
Resonant bar	1 - 200 kHz	tuff	201	13
		granite	120	6
Waveform inversion	1 - 200 kHz	tuff	40	15
		granite	150	15
Ultrasonic velocity	700 kHz	tuff	40	55
		granite	40	55

In order to compare the data collected with each of the four methods as a function of frequency, it is necessary to account for the differences in strain amplitude, sample geometry, and sample size. All the tests were unconfined at atmospheric pressure and room temperature. The ultrasonic velocity, resonant bar, and waveform inversion measurements utilize pulse propagation techniques with peak strain amplitudes on the order of 10^{-8} to 10^{-6} . These data were compared with hysteresis loops that had strain amplitudes less than 5×10^{-6} acquired from the cyclic loading tests. The cyclic loading experiments were conducted in a servo-controlled loading frame with an axial preload of 1 MPa. The cyclic loading tests were completed first. The sample then was subdivided into smaller specimens for the wave propagation measurements.

2.1 Cyclic Loading (Hysteresis loop)

Young's modulus and Q_E^{-1} were determined from steady state stress-strain data measured during cyclic loading experiments. A continuous sinusoidal axial load was applied to cylindrical samples. The strain was computed from the average of three axial displacement transducers mounted on circumferential rings positioned 1 inch from each sample end. Up to 200 cycles were collected at a given frequency. Young's modulus and Q_E^{-1} were determined from the Fast Fourier Transforms of the stress and strain sinusoids. The modulus was computed from the peak amplitudes of the stress and strain spectrums at a given frequency. Q_E^{-1} was computed in the frequency domain from the complex Young's modulus as given in equation (2). Mechanical and electronic system losses were determined by conducting identical tests on a low loss standard (aluminum) with the same cross-sectional area and length as the rock specimens.

2.2 Resonant Bar

Young's modulus and Q_E^{-1} were determined from the resonance peak excited in thin rods. Samples were cut into square bars with a length to diameter ratio greater than 10. A standing extensional wave was generated using piezoelectric crystals mounted on the sample ends. Extensional velocity was computed from the center frequency of the resonant peak and the sample length. Young's modulus was then computed from the velocity and sample density. Q_E^{-1} was computed from the center frequency and half-power bandwidth of the resonance peak. The mass of the piezoelectric crystals and sample jacket were accounted for in a correction factor described by Lucet et al., (1991). Tittmann et al., (1977) and Lucet et al., (1991) discussed this technique in further detail.

2.3 Waveform Inversion

Elastic wave velocities and attenuation were determined jointly for frequencies ranging from 1 to 200 kHz. The technique involves measuring waveforms in two cylindrical bars of the same material, but of different length. First, roughly estimated bar velocity and Poisson's ratio were used to propagate the waveform observed in the shorter bar to the length of the longer bar. Guided by the velocity model, the velocity dispersion curve was then computed from the model, the measured phase difference between the propagated waveform and the measured waveform within the longer bar. Using Rayleigh's solution for the low frequency phase velocities, the low

frequency portion of the dispersion curve was inverted to obtain an accurate estimate of the bar velocity and Young's modulus.

Q_E^{-1} was computed in the following steps. The waveform of the shorter bar was theoretically continued to the length of the longer bar to match the measured waveform. The waveform inversion then was performed to minimize the amplitude difference between the two waveforms, from which Q_E^{-1} was computed. For further detail on the waveform inversion technique, see Tang (in press, 1992).

2.4 Ultrasonic Measurements

Dynamic Young's modulus was determined from the sample density and the measured ultrasonic compressional and shear wave velocities. Q_E^{-1} was computed from values of Q_P , Q_S and Q_E determined with the spectral ratio technique using a low loss standard (aluminum) for comparison with the rock (Toksoz et al., 1979). The velocity measurements were performed in a benchtop apparatus capable of measuring compressional and two orthogonally polarized shear waves.

3 EXPERIMENTAL RESULTS

3.1 Topopah Spring Member welded tuff

The effects of frequency on Young's modulus and Q_E^{-1} for room dry and water saturated tuff are shown in Figures 1a and 1b. Young's modulus of the saturated tuff is typically lower than the dry values by approximately 5% for all frequencies. The modulus for the dry condition increases slightly, less than 2%, with frequency between 0.01 and 50 Hz. The saturated modulus increases less than 6% in the same range. The modulus computed from the ultrasonic measurements is in very good agreement with these values. The moduli determined at the first mode of the resonant bar are shown. The dry and saturated moduli were 40.2 and 40.6 GPa, respectively. The waveform inversion measurements resulted in dry and saturated moduli ranging from 35.8 to 37.4 GPa and 35.3 to 36.1 GPa, respectively.

Q_E^{-1} is shown as a function of frequency in Figure 1b. For the dry condition, Q_E^{-1} is relatively low and independent of frequency below 50 Hz. In the saturated tuff, Q_E^{-1} increased significantly above 10 Hz. As frequency increases, Q_E^{-1} for the saturated condition increases at a greater rate than for the dry condition. The Q_E^{-1} in dry tuff is consistently lower than that of the saturated tuff at any frequency. The resonant bar and waveform inversion Q_E^{-1} are not comparable over the same frequencies. The waveform inversion Q_E^{-1} is larger for both dry and saturated measurements than correlating values below 50 Hz, as well as being larger than the resonant bar data.

The effect of strain amplitude on room dry and water saturated tuff is shown in Figures 2a and 2b. Young's modulus and Q_E^{-1} do not exhibit a significant dependence on strain amplitude. The modulus in the saturated tuff is consistently lower by approximately 5% than that of the dry condition. Q_E^{-1} is slightly larger (up to a few percent) in the saturated sample.

3.2 Sierra White granite

The effects of frequency on Young's modulus and Q_E^{-1} for room dry and water saturated granite are shown in Figures 3a and 3b. The cyclic loading, first mode of the resonant bar, and ultrasonic moduli are shown in Figure 3a. Young's modulus was not measured with the waveform inversion technique for the granite. In the dry state, Young's modulus slightly increases below 50 Hz, then remains relatively constant with increasing frequency. In saturated samples, the modulus increases significantly from 30.3 GPa at 0.01 Hz to 37.3 GPa at 100 Hz. The resonant bar dry and saturated values are within a percent of each other. The ultrasonic saturated modulus is almost double that of the cyclic load value at 0.01 Hz.

The cyclic loading, all modes of the resonant bar, waveform inversion, and ultrasonic Q_E^{-1} are presented as a function of frequency in Figure 3b. Q_E^{-1} was only measured with the waveform inversion technique in the room dry condition. For dry granite, Q_E^{-1} is low, and increases slightly with increasing frequency. Q_E^{-1} for the saturated condition exhibits a pronounced frequency dependence and is significantly greater than Q_E^{-1} for the dry state at all frequencies, excluding the ultrasonic data point. Q_E^{-1} increases by a factor of six between 0.01 and 100 Hz. In contrast, the resonant bar data show a decrease with increasing frequency between 10 - 100 kHz.

Strain amplitude affects the modulus and Q_E^{-1} for both the room dry and saturated conditions as shown in Figures 4a and 4b. In Figure 4a, the room dry and saturated samples exhibit a decrease in modulus with increasing strain amplitude. The changes were most pronounced for strains above 5×10^{-6} . An increase in strain amplitude produces an increase in Q_E^{-1} , as depicted in Figure 4b. For the dry condition, the attenuation increases significantly at strain amplitudes above 5×10^{-6} . For the saturated condition, the rate of increase in Q_E^{-1} is large at strain amplitudes as low as 1×10^{-6} . It appears that the rate of increase at high strain amplitudes is approximately the same for the dry and saturated states.

4 DISCUSSION

Four techniques were used to measure Young's modulus and Q_E^{-1} as a function of frequency, strain amplitude, and saturation for specimens of the Topopah Spring Member welded tuff and Sierra White granite. In general, the different techniques produced similar modulus data. The differences observed in the attenuation values obtained from the waveform inversion and resonant bar techniques on the tuff samples are believed to be the result of sample inhomogeneity. Tuff is a highly heterogeneous rock yielding a large scatter in rock mechanics properties (Price et al., 1987). The inhomogeneities in the tuff (e.g., pumice fragments, vapor phase altered zones, lithics, lithophysae) range in size from microscopic to several centimeters. The relatively small subsamples taken for these techniques from the cyclic loading sample could very easily have contained different quantities of inhomogeneities, therefore creating a scatter in the resulting attenuation data for the two techniques. The Sierra White granite, however, is a relatively homogeneous rock with uniform grain size on the order of 0.5 mm (Martin et al. 1990). As a result, the attenuation data are much more consistent between techniques.

4.1 Young's Modulus: The effect of frequency and water saturation

In general, Young's modulus shows a slight frequency dependence in room dry tuff and granite. The moduli for the saturated tuff typically are less than the corresponding room dry measurement. The reduction in modulus for the saturated granite is greater, especially at lower frequencies. The reduction in modulus for the saturated state can be attributed to the reduction of surface energy along the grain boundaries, microcracks, and pores within the rock (Murphy, 1982; Bulau et al., 1984; Murphy et al., 1984). The reduction in modulus is more pronounced for the granite than for the tuff. This is due, at least in part, to the pore geometry. The granite is characterized by low aspect ratio cracks (Martin et al. 1990), whereas the pore structure of the welded tuff consists predominantly of ellipsoidal pores and lithophysal zones (Price et al., 1987).

The frequency dependence of the modulus can be attributed to fluid flow within the sample. When the cyclic loading rate exceeds the time constant for fluid diffusion within the pore space, the specimen begins to stiffen due to the compression of the pore water. In turn, the effective modulus increases. The point at which the relative stiffening occurs is directly related to the sample diameter, pore geometry, and the boundary conditions for fluid flow within the specimen (Spencer, 1981; Dunn, 1987).

4.2 Attenuation: The effect of frequency and water saturation

The Q_E^{-1} for both rock types in the room dry condition is relatively low and is, at least to the first order, independent of frequency. These observations are consistent with previous data (Spencer, 1981, Winkler et al, 1979, Murphy, 1984). The resonant bar and waveform inversion data exhibit a significant difference in Q_E^{-1} that is attributed to sample heterogeneity. Lucet et al. (1991) have shown that sample heterogeneity significantly affects the modulus and attenuation measurements. For the granite, the waveform inversion and resonant bar data yield nearly identical results.

Water saturated welded tuff and granite show larger Q_E^{-1} than the room dry specimens at nearly all frequencies. Furthermore, the attenuation is frequency dependent. At frequencies less than 1 Hz, the dry and saturated attenuation for tuff are nearly the same. However, at higher frequencies between 1 and 100 Hz, the Q_E^{-1} increases nearly five fold. Between 10 and 200 kHz, resonant bar and waveform inversion techniques display a consistently greater attenuation for the saturated condition than the dry. However, comparisons between the measurements at these frequencies do not yield consistent results; as with the room dry condition, differences are most likely due to sample heterogeneity.

The data for saturated granite are strongly frequency dependent. At frequencies between 0.01 and 100 Hz, Q_E^{-1} increases from 0.012 to 0.060. This increase can be attributed to a number of mechanisms. The fluid flow in the pores is strongly frequency dependent and can give rise to attenuation. Models have been proposed by Walsh, (1969), Mavko and Nur (1979), O'Connell and Budiansky (1977), White (1986), and Gardener (1962) to explain the experimental data; attenuation is attributed to the relative motion between the fluid and pore. As the loading frequency increases, the rate of fluid flow increases and viscous losses control the attenuation. Once the deformation rate is significantly greater than the pore fluid response, stiffening occurs and attenuation decreases. This effect is clearly demonstrated in the resonant bar data for granite. The data set for tuff does not exhibit the stiffening by fluid or the

corresponding decrease in attenuation. Fluid flow is governed by the boundary conditions imposed by the experimental set up, the sample geometry, and the pore geometry. All the specimens were tested under drained conditions. For the small diameter tuff specimens with a relatively high porosity and rounded pores, flow in and out of the pores and stiffening of the fluid was minimal.

4.3 Effect of strain amplitude on modulus and attenuation

The effect of strain amplitude on Young's modulus and seismic wave attenuation has been considered by a number of investigators (Mavko, 1979; Winkler et al., 1979). For rocks with low aspect ratio cracks the modulus has been shown to decrease with increasing strain amplitude. Several models have been proposed to explain this decrease. Walsh, (1969), Mavko (1979), and Winkler et al., (1979) have proposed frictional mechanisms in which sliding on microcracks dissipates energy, observed as attenuation. Alternative mechanisms based on changes in surface energy and movement of fluid films in partially saturated rocks have been proposed by Spencer, (1981), Mavko and Nur, (1979), Bulau et al., (1984) and Murphy et al. (1984). For the granite, a decrease in modulus was observed with increasing strain amplitude. The water saturated specimens showed a similar trend although the modulus was reduced by approximately 30%. In contrast, Young's modulus for the tuff showed no strain amplitude dependence for either the dry or saturated conditions. For granite, the attenuation increases markedly as the strain amplitude is increased from 5×10^{-7} to 5×10^{-4} . The transition to frequency dependent attenuation occurs at strain amplitudes approaching 10^{-5} for dry granite and at 10^{-6} for the saturated granite. The frequency shift observed for the granite is most likely related to flow within the pores. The absence of any strain amplitude dependence in any of the saturated specimens of the welded tuff is most likely due to the fact that flow mechanisms will not be dominant at 0.1 Hz in tuff because of its unique pore geometry. The data collected on these two samples are not sufficient to distinguish between the proposed frictional mechanism or surface diffusion mechanism for the strain amplitude dependence of attenuation.

REFERENCES

- Bulau, J.R., B.R. Tittmann, M. Abdel-Gawad, and C. Salvado, 1984, The role of aqueous fluids in the internal friction of rock: *J. Geophys. Res.*, 89(B6), 4207-4212.
- Dunn, K.J., 1986, Acoustic attenuation in fluid-saturated porous cylinders at low frequencies: *J. Acoustic. Soc. Am.* 79(6), 1709-1721.
- Dunn K.J., 1987, Sample boundary effect in acoustic attenuation of fluid-saturated porous cylinders: *J. Acoustic. Soc. Am.* 81(5), 1259-1266.
- Gardner, G.H.F., 1962, Extensional waves in fluid-saturated porous cylinders: *J. Acoustic Soc. Am.* 34(1), 36-40.
- Gordon, R.B., and L.A. Davis, 1968, Velocity and attenuation of seismic waves in imperfectly elastic rock: *J. Geophys. Res.*, 73, 3917-3935.
- Lucet, N., P.N. Rasolofosaon, and B. Zinsner, 1991, Sonic properties of rocks under confining pressure using the resonant bar technique: *J. Acoust. Soc. Am* 89(3), 980-990.

- Martin, R.J.,III, K.B. Coyner, and R.W. Haupt, 1989, Physical property measurements on granites related to the Joint Verification Experiment: DARPA Report F19628-89-C-0097.
- Mavko, G.M., 1979, Frictional attenuation: An inherent amplitude dependence: J. Geophys. Res., 84, 4769-4775.
- Mavko, G. and A. Nur, 1979, Wave attenuation in partially saturated rocks: Geophysics, 44, 161-178.
- Murphy, W.F.,III, 1982, Effects of partial water saturation on attenuation in Massillon sandstone and Vycor porous glass: J. Acoust. Soc. Am., 71(6), 1458-1468.
- Murphy, W.F.,III, K.W. Winkler and R.L. Kleinberg, 1984, Frame Modulus Reduction in Sedimentary Rocks: The Effect of Adsorption on Grain Contacts: J. Geophys Res. Lett, 9, 805-808.
- O'Connell, R.J. and B. Budiansky, 1977, Viscoelastic properties of fluid-saturated cracked solids: J. Geophys. Res., 82, 5719-5735.
- Price, R.H., J.R. Connolly, and K. Keil, 1987, Petrologic and mechanical properties of outcrop samples of the Welded, Devitified Topopah Spring Member of the Paintbrush Tuff: Sandia Report, SAND86-1131 UC-70.
- Paffenholz, J. and H. Burkhardt, 1989, Absorption and modulus measurements in the seismic frequency and strain range on partially saturated sedimentary rocks: J. Geophys Res., 94, 9493-9507.
- Spencer, J.W., 1981, Stress relaxations at low frequencies in fluid-saturated rocks: Attenuation and modulus dispersion: J. Geophys. Res., 86, 1803-1812.
- Tang, X., 1992, A waveform inversion technique for measuring elastic wave attenuation in cylindrical bars: submitted to Geophysics. (in press).
- Tittmann, B.R., L. Ahlberg, H. Nadler, J. Curnow, T. Smith and E.R. Cohen, 1977, Internal friction quality-factor Q under confining pressure: Proceedings of the Eighth Lunar Science Conference, 1209-1224.
- Toksoz, M.N., D.H. Johnston, and A. Timur, 1979, Attenuation of seismic waves in dry and saturated rocks: I. Laboratory measurements: Geophysics, 44, 681-690.
- Toksoz, M.N., and D.H. Johnston, 1981, Seismic Wave Attenuation: Geophysics reprint series, No. 2.
- Walsh, J.B., 1969, Seismic wave attenuation in rock due to friction: J. Geophys. Res., 71, 2591-2599.
- White, E. J., 1986, Biot-gardner theory of extensional waves in porous rocks: Geophysics, 51, 742-745.
- Winkler, D., A. Nur, and M. Gladwin, 1979: Friction and seismic attenuation in rocks. Nature, 277, 528-531.

Figure 2a

Figure 2b

Figure 3a

Figure 3b

Figure 4a

Figure 4b

Figure 1a

Young's modulus plotted as a function of frequency for the Topopah Spring Member welded tuff. Data are presented for dry and water saturated conditions.

Figure 1b

Q_E^{-1} plotted as a function of frequency for the Topopah Spring Member welded tuff. Data are presented for dry and water saturated conditions.

Figure 2a

Young's modulus plotted as a function of strain amplitude for the Topopah Spring Member welded tuff. Data are measured from 0.1 Hz hysteresis loops and are presented for dry and water saturated conditions.

Figure 2b

Q_E^{-1} plotted as a function of strain amplitude for the Topopah Spring Member welded tuff. Data are measured from 0.1 Hz hysteresis loops and are presented for dry and water saturated conditions.

Figure 3a

Young's modulus plotted as a function of frequency for Sierra White granite. Data are presented for dry and water saturated conditions.

Figure 3b

Q_E^{-1} plotted as a function of frequency for Sierra White granite. Data are presented for dry and water saturated conditions.

Figure 4a

Young's modulus plotted as a function of strain amplitude for Sierra White granite. Data are measured from 0.1 Hz hysteresis loops and are presented for dry and water saturated conditions.

Figure 4b

Q_E^{-1} plotted as a function of strain amplitude for Sierra White granite. Data are measured from 0.1 Hz hysteresis loops and are presented for dry and water saturated conditions.

END

**DATE
FILMED
5106192**